



# Exclusive Hadronic Reactions at High $Q^2$ ( $90^\circ$ ) and Polarization Phenomena, An Experimental Proposal

F. Myhrer

Department of Physics and Astronomy, University of South Carolina,  
Columbia, SC29208

## Abstract.

Arguments are presented for the expected behaviour of  $\pi N \rightarrow \pi N$  scattering and the  $\bar{p}p \rightarrow \pi^- \pi^+$  reaction at high energy and large scattering angles. The annihilation reaction has close to maximal asymmetry ( $\approx 1$ ) for  $p_{lab} \lesssim 2.2$  GeV/c. As will be presented for fixed ( $90^\circ$ ) angle this large asymmetry will not become zero but will start to oscillate with energy at higher energies and large  $Q^2$  when perturbative QCD becomes applicable. This is due to the energy dependence of a QCD phase difference between the independent quark-quark scattering (Landshoff) and short-distance processes at high but not asymptotic energies. A consequence of the existence the Landshoff process is that even if helicity is conserved at the quark level ( $m_q = 0$  MeV), helicity does not have to be conserved on the hadronic level. We will discuss the implications for spin observables in  $pp$  elastic scattering and argue that these QCD phenomena are easier to explore theoretically in the  $\pi N \rightarrow \pi N$  scattering and/or in the crossed channel reaction  $\bar{p}p \rightarrow \pi^- \pi^+$  where the analysis is simpler because these two processes have only two helicity amplitudes.

## 1 Introduction

For short-distance perturbative QCD exclusive hadronic scattering processes the quarks are all connected by high  $Q^2$  gluons and all quark propagators are far off-shell [1].

Figure 1: Illustrations of contributions to  $\pi N \rightarrow \pi N$  scattering amplitudes. On the left an example of a short-distance contribution to  $f_{SD}$ . On the right a contribution to the Landshoff amplitude  $f_L$ . The dashed lines signify that this quark-quark scattering does not have to occur in the same plane as the other scattering.

This means the short distance amplitudes  $f_{SD}$  are all real and no polarization effects are expected. However, the Landshoff amplitudes  $f_L$  will contribute to the same exclusive hadronic scattering processes [2]. In the  $f_L$  amplitudes the hard gluons are also at high  $Q^2$  but the two independent quark-quark scatterings can take place in two parallel scattering planes leading to the same final hadrons. The distance between these two independent quark-quark scatterings are determined by the sizes of the hadrons involved. The only requirement is that after the hard (high  $Q^2$ ) scattering the final quarks (antiquarks) move parallel with roughly the same speed to be able to form the final hadrons as illustrated for  $\pi N \rightarrow \pi N$  scattering in Fig.1. The distance between the two quark-quark scatterings implies one has a relative angular momentum which can couple to the spin and give for the hadronic reaction at least a  $L \cdot S$  amplitude. Such an amplitude violates helicity conservation on the hadronic level [4]. Or said differently, since the Landshoff amplitudes contain soft QCD processes where a propagator is (almost) on-shell (Sudakov form factors), called "the Landshoff pinch" in the review by Mueller [3], the amplitudes  $f_L$  will in general be complex. As a consequence we will observe polarization phenomena in hadronic reactions.

## 2 Asymmetries

### 2.1 The Reaction $\bar{p}p \rightarrow \pi\pi$

Figure 2: (a) An example of short-distance QCD diagram to order  $\alpha_s^4$  for the process  $\bar{p}p \rightarrow \pi\pi$ . The diagram has an  $s^{-3}$  dependence. (b) An example of diagrams for large-angle Landshoff process for the same reaction of order  $\alpha_s^3$ . The timelike gluon and one quark are off-shell and the diagram gives an  $s^{-5/2}$  behavior when we neglect radiative corrections.

First let us concentrate on the  $\bar{p}p \rightarrow \pi^-\pi^+$  reaction which has a large analysing power,  $A_{0n} \approx 1$  for  $p_{lab} \lesssim 2.2$  GeV/c [5, 6, 7] as discussed at this workshop [8, 9]. If helicity is conserved on the hadronic level at very high energy, then  $A_{0n}$  should be zero at these energies. This is correct *only if* the short distance amplitude  $f_{SD}$  illustrated in Fig. 2a acts alone. However, as discussed in Ref. [10], the Landshoff amplitude,  $f_L$  illustrated in Fig. 2b, will contribute as well. Including the radiative corrections  $f_L$  will be at least of order  $\alpha_s^4$  like  $f_{SD}$  illustrated in Fig. 2a, but  $f_L$  will fall off with increasing energy like  $s^{2.85}$ , i.e., slower than  $f_{SD}$ .

The elementary quark-quark scattering amplitude has an energy-dependent phase, as inferred by Ralston and Pire [11] and calculated in perturbative QCD by Sen [12]. Its analytic form is

$$\Phi \sim \frac{\pi}{6} \ln \ln (Q^2/\Lambda^2) \quad (1)$$

where  $\Lambda \approx 100$  MeV. Ralston and Pire used this phase in their phenomenological hadronic Landshoff amplitudes to describe the energy oscillations of the scaled  $pp$  elastic  $90^\circ$  cross section. They needed a

constant  $a$  ( $\approx 50$ ) in front of the double log instead of  $\pi/6$  of eq.(1) to reproduce the observed (see Fig. 3) period of the energy oscillations in the scaled  $pp$  elastic  $90^\circ$  scattering. Botts and Sterman analysed this phase factor in hadronic reactions and found the expression [13]

$$\Phi = a \ln \left( \frac{\ln s/\Lambda^2}{\ln 1/(b\Lambda)^2} \right) + \text{constant}, \quad (2)$$

where the constant  $a$  in perturbative QCD is  $\pi/6$ , and  $\Lambda = 100$  MeV as before. The impact parameter  $b$  can be thought of as the average distance between the independent quark-quark scatterings. It has the following energy dependence [13]

$$b\Lambda = (\sqrt{s}/\Lambda')^{-\tau} \quad (3)$$

where  $\tau \approx 0.7$  for three flavors of quarks. As discussed by Botts and Sterman [13, 14] the phase eq.(2) should become independent of energy at asymptotic energies ( $s \rightarrow \infty$ ).

Figure 3: The elastic  $pp$  cross section at  $90^\circ$  scaled by  $s^{10}$  as a function of energy. Figure taken from Carlson *et al.* [10].

## 2.2 Elastic $pp$ Scattering

If we apply these ideas to  $pp$  elastic scattering we can show that not only the oscillations in the scaled cross section at  $90^\circ$ , see Fig. 3, can be reproduced (see here Ref. [11]), but also the spin-correlation observable  $A_{nn}$  at  $90^\circ$  can be described [10]. The phenomenological arguments leading to these results are following Ref. [10]: For elastic  $pp$  scattering the five helicity amplitudes  $M_i$  ( $i = 1, \dots, 5$ ) are of the form (the energy scale is factored out in  $\phi_i$ ):

$$\phi_i \propto s^{-4} M_i = s^{-4} (B_i + C_i s^{0.2} e^{i[\Psi_i + \delta_i]}), \quad (4)$$

where  $B_i$ , which originates from the short distance  $pp$  amplitude  $M_{SD}$ ,  $C_i$  from the Landshoff amplitude  $M_L$ , and  $\delta_i$  are real constants. The phase is deduced from eqs.(2) and (3) to be

$$\Psi_i = a \ln \left( \frac{\ln(s/\Lambda^2)}{\ln(s/\Lambda_i^2)} \right). \quad (5)$$

The energy dependence of  $A_{nn}$  at  $90^\circ$  is then understood to be a "beating" of the different energy-periods in the phases of the helicity amplitudes above [10]. With the interplay of the two amplitudes,  $M_{SD}$  and  $M_L$ , it is not difficult to reproduce the spin observables in  $pp$  elastic scattering. However, since  $pp$  elastic scattering has in general *five* helicity amplitudes, there is too much freedom in fitting data. Only for  $90^\circ$  c.m. scattering do the expressions simplify since  $\phi_5 = 0$  and  $\phi_4 = -\phi_3$  so we have only three independent helicity amplitudes.

### 3 Ideas for experimental proposals

To examine if this phenomenological analysis is reasonable, it would be preferable to test the predictions in the two reactions  $\pi N \rightarrow \pi N$  and  $\bar{p}p \rightarrow \pi\pi$ . Each of these reactions are described by *only two* helicity amplitudes, the helicity non-flip  $f_{++}$  and the helicity flip  $f_{+-}$  amplitude. Furthermore, these measurements can be done at existing facilities like *AGS* at Brookhaven National Laboratory or at Fermilab, and certainly at the proposed facilities like *SuperLEAR* or *KAON*.

In terms of these two helicity amplitudes the cross section and the asymmetry are given as

$$d\sigma/d\Omega = |f_{++}|^2 + |f_{+-}|^2 \quad \text{and} \quad A_{0n} = 2\Im m(f_{++}^* f_{+-})/(d\sigma/d\Omega). \quad (6)$$

For the  $\bar{p}p \rightarrow \pi\pi$  reaction the short-distance real amplitude  $f_{SD}$  contributes only to  $f_{+-}$ , whereas the Landshoff amplitude  $f_L$  contributes to both helicity amplitudes. The energy dependences of the two amplitudes are as follows:

$$f_{SD} \propto s^{-3} \quad \text{and} \quad f_L \propto s^{-2.85} \quad (7)$$

meaning the Landshoff amplitude will also dominate at high enough energies for these reactions.

For both reactions some data already exist for the scaled cross sections  $s^8 d\sigma/d\Omega$  at  $90^\circ$ . For the reaction  $\bar{p}p \rightarrow \pi^-\pi^+$  data exist for momenta up to  $p_{lab} = 6.2$  GeV/c [15, 16] as shown in Fig. 4 taken from Ref. [10]. The elastic  $\pi N \rightarrow \pi N$  scattering at  $90^\circ$  have been measured for momenta as high as 30 GeV/c [17]. In Fig. 5 we show the scaled cross section data for the  $\pi N \rightarrow \pi N$  scattering, a figure taken from G. Blazey's thesis [18]. Unfortunately the highest energy measurement at  $p_{lab} = 30$  GeV/c has uncertainties too large to be useful in this discussion and is not shown in this figure. As is clear from Figs. 4 and 5, a few measurements at different energies with reasonable statistics are needed to establish the possible oscillatory pattern of the scaled cross section.

Figure 4: The cross section for  $\bar{p}p \rightarrow \pi^-\pi^+$  at  $90^\circ$  scaled by  $s^8$  as a function of  $\ln s$ . Figure taken from Ref. [10].

Figure 5: The cross section for elastic  $\pi N \rightarrow \pi N$  scattering at  $90^\circ$  scaled by a factor  $s^8$ . Figure taken from Ref. [18].

The question being asked is if both of these scaled cross sections oscillate with energy similar to what is observed for  $pp$  elastic scattering, see Fig.3. If this is found to be the case then a further confirmation of the ideas presented here would be to see similar energy oscillations in  $A_{0n}$  for the same two reactions. Experimentally, the annihilation reaction might be better since the asymmetry at low energies  $p_{lab} \approx 2$  GeV/c is very large [5, 6, 7]. However, we do expect the geometric hadronic impact parameter ideas used to explain this large asymmetry [8, 9] to break down when the perturbative QCD regime of exclusive hadronic reactions is reached at higher energies [10]. The onset of the perturbative QCD regime may be signaled by a significant change in the energy and angular variation of the asymmetry, for example, the large  $A_{0n}$  at  $90^\circ$  will become smaller and start to oscillate with increasing energy if the QCD phenomenology outlined above is reasonable.

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